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Keywords:	Pollen, Chironomids, Diatoms, Plant macrofossils, Driving factors, Northern boreal Fennoscandia

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Abstract

Four biotic proxies (plant macrofossils, pollen, chironomids, and diatoms) are employed to quantitatively reconstruct variations in mean July air temperatures (T_{jul}) at Lake Loitsana (northern Finland) during the Holocene. The aim is to evaluate these temperature reconstructions and to compare the timing of highest T_{jul} in the individual reconstructions. The reconstructed T_{jul} values are evaluated in relation to local-scale/site-specific processes associated to the Holocene lake development at Loitsana, as these factors have been shown to significantly influence the fossil assemblages found in the Lake Loitsana sediments. While pollen-based temperatures follow the classical trend of gradually increasing early Holocene T_{jul} with a mid-Holocene maximum, the aquatic/wetland assemblages reconstruct higher than present T_{jul} already during the early Holocene, i.e. at the peak of summer insolation. The relatively low early Holocene July temperatures recorded by the terrestrial pollen are the result of site-specific factors possibly combined with a delayed response of the terrestrial ecosystem compared to the aquatic ecosystem. Our study shows that all the reconstructions are influenced at least to some extent by local factors, and highlights the benefit of using multi-proxy data in Holocene climate reconstructions.

Introduction

Reconstructing Holocene temperatures through the use of quantitative methods has received considerable attention in the past decades (e.g. Juggins, 2013). While this has allowed to explore their potential and detect strengths and weaknesses of the various quantitative reconstruction tools available (Birks et al., 2010; Juggins and Birks, 2012), more detailed studies of underlying drivers and reasons for divergent temperature reconstructions yielded from different biotic proxies are still needed. The reasons for the differences are mainly related to the transfer-function approach itself due to the complex nature of biotic response to environmental change (Anderson, 2000; Velle et al., 2010, 2012; Brooks et al., 2012; Juggins, 2013). Recent studies discussing the effect of various parameters on the reconstructed temperatures, e.g. choice of calibration-set or regression method, have further emphasized the complexity and sensitivity of the transfer-function approach, suggesting that additional caution should be exercised in the interpretation of transfer-function-based climate reconstructions (Salonen et al., 2012; 2013a, b; Juggins, 2013; Luoto et al., 2014). Furthermore, the classical view of low summer temperatures during the first millennia of the Holocene and a mid-Holocene maximum warming in northern Europe has recently been challenged. While this traditional view has been based mainly on pollen-inferred climate reconstructions (Seppä and Birks, 2001; Salonen et al., 2011; Renssen et al., 2012), fossil assemblages of plant macrofossils and insect remains often suggest high summer temperatures already during the earliest Holocene (Brooks and Birks, 2001; Jones et al., 2011; Paus et al., 2011; Väliranta et al., 2011b; Birks et al., 2012; Luoto et al., 2014; Väliranta et al., 2015). Thus, the present study based on a multi-proxy approach can further increase our understanding in the applicability of biotic proxy-based temperature inferences

especially in the boreal bio-climate zone of Fennoscandia, where detailed records are still scarce.

In this paper, Holocene mean July air temperature (T_{jul}) reconstructions based on four biological assemblages (plant macrofossils, pollen, chironomids, and diatoms) are compared and evaluated in the light of local-scale and site-specific processes, as these factors have been shown to significantly influence fossil assemblages extracted from lake sediments (Velle et al., 2005; Anderson et al., 2008; Shala et al., 2014). While the plant macrofossil-based reconstructions make use of the presence of certain indicator taxa and yield a minimum T_{jul} only (Väliranta et al., 2015), the other three T_{jul} reconstructions are based on the multivariate transfer-function approach in which both the most likely past temperature and the sample-specific reconstruction error are estimated. The compositional distance between fossil samples and their closest modern analogues in the calibration-set, the temperature optima of the dominating taxa as well as the distribution of calibration sites along the temperature gradient of the calibration-set are used to compare and evaluate the reconstructions.

Study site

The coring site is situated in the eastern part of Lake Loitsana, at Sokli, NE Finland (67°48'17"N, 29°16'56"E; 214 m a.s.l.; Fig. 1 A-B). Regional present-day vegetation consists of northern boreal forest with birch (*Betula pubescens* and *B. pendula*), pine (*Pinus sylvestris*) and spruce (*Picea abies*) as the dominating tree species. The mean annual temperature in the area is approximately -1 °C, with a January mean of -13.8 °C, and a July mean of 13.4 °C. Mean annual precipitation is approximately 550 mm (Fig. 1C). The underlying bedrock consists of a Palaeozoic carbonate-rich magma intrusion

(Sokli Carbonatite Massif), which is surrounded by bedrock consisting of crystalline rocks of the Precambrian Shield (Vartiainen, 1980).

Lake Loitsana is situated in a former meltwater channel associated with NW-SE oriented esker chains. The lake area is 8 ha, water depth of 1–2 m, water pH c. 7.4, and autumnal total phosphorus (TP) concentration c. 19-25 $\mu g\ l^{-1}$ (Finnish Environmental Institute, 2010). The lake is currently mainly fed by groundwater inflow and by limited surficial input from a small stream in the NW part of the lake. It has also one narrow outflow. An extensive aapa mire complex borders the lake to the south (Fig. 1B).

[insert Figure 1.]

The general lake development history and associated processes were described and discussed in Shala et al. (2014) and general regional vegetation development in Salonen et al. (2013a). Shala et al. (2014) identified six lake stages with associated local processes, each affecting the different biological assemblages during various periods (Fig. 2). These local stages were; a deep glacial lake (Stage 1), glacial lake drainage resulting in a shallow glacial lake (Stage 2), the formation of Lake Loitsana (Stage 3) with a morphometric eutrophication (Stage 3A) and a period of stratification (Stage 3B), nearby wetland development with changes in fluvial inflow (Stage 4), a river diversion (Stage 4B), a shallowing lake with limited surficial inflow (Stage 5), and a more or less isolated groundwater-fed lake (Stage 6). A summary of the Holocene lake development as well as regional vegetation development is presented in Fig. 2. This summary is expanded in the Supplementary information, where a detailed pollen/macrofossil diagram (Supplementary Figure 1) is also included.

[insert Figure 2.]

Materials and methods

Fossil data

Down-core fossil data were obtained from nine meters of lacustrine sediment, collected with a Russian peat corer from the ice-covered Lake Loitsana in spring 2008. The core was subsampled with a resolution of 1 cm between 0 and 735 cm consisting of organic-rich sediments and at 5 cm resolution between 735 and 900 cm, where the sediment was of minerogenic origin. Fossil analyses (plant macrofossils, pollen, chironomids, and diatoms) were performed at intervals of 3–20 cm in the organic-rich sediment and 5–10 cm in the underlying minerogenic unit. Details on the different analytical procedures are presented in Shala et al. (2014).

Quantitative reconstructions

Holocene T_{jul} reconstructions based on plant macrofossils (henceforth T_{julM}), pollen (T_{julP}), chironomids (T_{julC}), and diatoms (T_{julD}) were performed on fossil data obtained from the Loitsana sediment sequence.

Plant macrofossils. The T_{julM} reconstruction method is adopted from Väliranta et al. (2015). The method is an implementation of the indicator-species method, with information on modern species distribution limits is combined with measured T_{jul} from the same grid cells (10x10 km) in Finland. First, the most indicative plant species is selected from the macrofossil assemblages. Next, modern species distribution observations (Lampinen et al., 2014) and a T_{jul} based on daily measurements (1970–2000) by the Finnish Meteorological Institute (Venäläinen et al., 2005), is used to estimate current taxon-specific minimum T_{jul} requirement. The taxon-specific minimum

T_{jul} requirement is a median value calculated over 5-6 observations along the taxon´s northernmost distribution limit. Estimates of past minimum T_{jul} are derived as the highest modern minimum T_{jul} requirement among the taxa found in the fossil sample.

Pollen, chironomids, and diatoms. T_{julP}, T_{julC}, and $T_{julD,}$ were reconstructed using two-component weighted averaging-partial least squares (WA-PLS; Ter Braak and Juggins, 1993) regression calibration models. Leave-one-out cross-validations (Birks, 1995) were used to calculate model performance statistics (Table 1), and estimated standard errors of prediction (eSEPs) for each fossil sample were obtained using random re-sampling (bootstrapping with 1000 iterations).

Table 1. Summary of calibration-set data, applied regression methods and model performance statistics for the different proxies. Two-component WA-PLS models were chosen for the pollen-, chironomid-, and diatom-based reconstructions. RMSEP = root mean square error of prediction.

Proxy	Pollen	Chironomids	Diatoms
No. of lakes in the calibration set	218	139	64
No. of taxa calibration set	127	117	370
Temperature range (°C)	9.0–17.3	7.9–17.1	7.9–15
Regression method	WA-PLS	WA-PLS	WA-PLS
Cross-validation approach	Jack-knifing	Jack-knifing	Jack-knifing
R2	0.884	0.880	0.882
Average bias (°C)	-0.018	0.005	0.032
Maximum bias (°C)	1.248	1.088	2.300
RMSEP (°C)	0.831	0.839	0.957

The modern analogue technique (MAT; Overpeck et al., 1985; Simpson, 2012) was used to assess the reliability of the reconstructions, by calculating the compositional distance (squared-chord distance) between fossil samples and their closest modern

analogues in the calibration set (CS) used. Qualitative estimates of the fit are made by comparing down-core distances to closest modern analogues to the distances found with the most-recent fossil samples, using increasing distance values as an indication of a worsening fit.

Species-response analysis was performed by using weighted averaging (WA; Birks et al., 1990) to extract the species temperature optima. As WA-PLS uses transformed species optima which are not readily assessable, we used the WA temperature optima and tolerances instead as a rough guideline to analyzing the trends and probable driving taxa in the reconstructions. All reconstructions and the analyses of compositional distances and species optima/tolerances were performed using the program C2 Data Analysis, version 1.7.2 (Juggins, 2007).

Calibration sets

Basic information about the three different CS's used in this study are summarised in Table 1.

The CS for T_{julP} consists of 218 lakes and 127 taxa (further details in Salonen et al., 2013a). The lakes are distributed along a latitudinal gradient from the Arctic Ocean coast to Lithuania and have a T_{jul} gradient of 9.0–17.3 °C.

The CS for T_{julC} consists of 139 lakes and 117 taxa (Luoto et al., 2014). The lakes are situated in northern Finland and distributed along a temperature gradient of 7.9-17.1 °C.

The CS for T_{julD} consists of 64 lakes and 370 taxa. The lakes are distributed along a temperature gradient of 7.9–14.9 °C in NW Finnish Lapland (Weckström and Korhola, 2001).

Results

Plant macrofossil-based reconstructions

The minimum T_{julM} estimations are based on the local presence of aquatic and wetland plants; *Glyceria lithuanica* (≥ 15.7 °C), and *Typha* seeds (≥ 15.7 °C), *Callitriche hermaphroditica* seeds (≥ 14.0 °C), *Callitriche cophocarpa* seeds (≥ 13.7 °C) and narrow-leaved *Potamogeton* species (≥ 13.6 °C). The results suggest that high T_{julM} (> present day values) prevailed already during the earliest part of the Holocene and temperatures at least as warm as today are indicated also for the rest of the Holocene (Fig. 3). After 10 100 cal. yrs BP no plant macrofossil remains indicating similarly high temperatures were found and this is reflected as a decline in T_{julM}.

[insert Figure 3.]

Transfer function-based reconstructions and modern analogues

Pollen-based reconstructions. Zone I (c. 10 800-10 570 cal. yrs BP) is characterized by rather low reconstructed T_{julP} values (c. 11.5 °C), which prevail throughout Zone II (10570-10200 cal a. BP). In Zone III, from c. 9000 cal. yrs BP onwards T_{julP} values gradually increase until c. 7000 cal. yrs BP, where it remains at ~14 °C (Fig. 3). Temperatures higher than present day (i.e. 13.4 °C) prevailed since then (Zones III and IV). The best fit between the fossil samples and modern analogues was recorded in Zone IV. In general, the fit is decreasing with increasing age. Cross-validation statistics for the pollen-based calibration model are good (Table 1). Furthermore, scattered occurrences of *Typha latifolia* and Nymphaceae pollen, which are currently distributed in the boreal zone of Finland, were noted until c. 6500 cal. yrs BP (Supplementary

Figure 1).

Chironomid-based reconstructions. During the earliest Holocene T_{julC} is c.12 °C (Fig. 4). Since c. 10 700 cal. yrs BP (Stage 1), T_{julC} values rapidly increase up to c.15 °C, where it remains throughout Stage 2 and 3A, until c. 9700 cal. yrs BP. This period is followed by a decline in T_{julC} (Stage 3B) with values below present day (13.4 °C) between c. 8700–6800 cal. yrs BP (Stage 4) and 6000–4300 cal. yrs BP (Stage 5). From c. 4300 cal. yrs BP (Stage 6) T_{julC} values were higher than present-day temperatures, with an increasing trend towards present. In general, the squared-chord distances of fossil samples to the closest modern analogue suggest a good fit. However, there appears to be a somewhat tendency to decreasing fit with increasing age (Fig. 4). Cross-validation statistics suggest that the model is strong, with similar performance compared to the T_{julP} model (Table 1).

[insert Figure 4.]

Diatom-based reconstructions. The reconstructed T_{julD} values are below the present-day temperature throughout the Holocene (Fig. 5). The T_{julD} temperature varies between 12.1–13.1 ºC with most values around 12.5 °C. The highest temperatures (around 13.1 °C) were reconstructed during Stages 1-3, i.e. prior to c. 8200 cal. yrs BP. A minor dip in T_{julD} (to ~12.4 ºC) can be observed in Stage 3A, at c. 9500 cal a BP. During Stage 4, 5 and 6, T_{julD} is relatively constant around 12.5 °C. The compositional fit between the fossil and modern samples is more or less constant throughout the Holocene, and there is no trend towards a deteriorating fit with increasing age. The model performance

statistics, however, are slightly weaker compared to the pollen and chironomid models (Table 1).

[insert Figure 5.]

Discussion

Evaluation of T_{jul} reconstructions

Plant macrofossils. The composition of plant macrofossils in sediment records is affected by factors such as water depth and distance to closest shore (e.g. Hannon and Gaillard, 1997; Väliranta 2006a, b), water chemistry and nutrient availability (e.g. Jackson and Charles, 1988), and temperature (e.g. Birks, 1991; Väliranta et al., 2015). Remains can be transported into lakes by wind, birds, inflowing streams, solifluction, and slope-wash (Birks, 2007).

In the Lake Loitsana sediment record, the presence of plant macrofossil remains appears to be mainly influenced by taphonomic factors such as distance to the shore, inflow of streaming water to the coring site and water depth (Shala et al., 2014). The near continuous presence of littoral zone species such as narrow-leaved *Potamogeton*, suggests that changes in water depth did not result in a marked alteration of the distance to the nearest shore, most likely due to the presence of an esker in the vicinity of the coring site with a steep side facing the lake.

In general, a high amount of terrestrial macrofossil remains in relation to littoral plant remains in sediment records reflects shallow conditions (Väliranta et al., 2006b). In Lake Loitsana, however, this relationship appears to be reflecting changes in inflow of streaming water. For example, a marked decline of terrestrial macrofossil remains, such as seeds and catkin scales from tree-type *Betula*, occurs at c. 6500 cal. yrs BP and

coincides with the redirection of the Soklioja rivulet (Supplementary Information). This further highlights that absence of certain species in the fossil record does not necessarily reflect its actual absence from the local vegetation (Birks, 1973; Hannon and Gaillard, 1997; Väliranta, 2005). Accordingly, the apparent decline in T_{julM} after 10 100 cal. yrs BP should not be interpreted as an indication of cooling.

Pollen. One advantage of using plant macrofossils in this study is that they confirm local presence of specific taxa, and are thus highly valuable also for the evaluation of pollen-based temperature reconstructions (Salonen et al., 2013a) allowing us to identify pollen or spore types, which are likely to be locally produced and not representative of the regional vegetation. In the pollen–climate CS used, the sites were carefully chosen to avoid littoral vegetation in order to restrict the amount of local pollen in the samples. This makes the pollen-reconstruction sensitive to taphonomic differences between the datasets resulting from e.g. changes in depositional settings. This, in turn, could affect the relative representation of regionally transported and locally produced pollen from e.g. a nearby shore or wetland and might cause an over-representation of locally produced pollen. The local origin of Cyperaceae, *Equisetum* and Gramineae (syn. Poaceae) following deglaciation and until 9200 cal. yrs BP is confirmed by presence of macrofossil remains (*Carex* seed, *Equisetum* remains, *Glyceria lithuanica*) and grass phytoliths. These taxa are more common in the tundra calibration sites and have thus low temperature optima in the CS (Salonen JS, personal observation). An overrepresentation of locally produced pollen could explain the poor compositional fit observed during the early Holocene as well as cause an underestimation of the reconstructed T_{julP}. Since 8000 cal. yrs BP occurrences of *Alnus*, *Filipendula* and long-

distance transported *Corylus* coincide with reconstructed temperatures above present day value (13.4 °C). Warmer temperatures (>13.4 °C) are generally driven by the occurrence of tree pollen (e.g. *Tilia*, *Ulmus*, *Corylus*, *Carpinus*, *Fraxinus*), which are presently only found in the southernmost part of the CS (Salonen JS, personal observation). The poor fit observed in the mid Holocene appears to be associated to high *Alnus* values. *Alnus* has a preference for moist habitats (Mossberg and Stenberg, 2003) and is a strong pollen producer (Bradshaw, 1981). Its pollen can be strongly over-represented when locally present (Tinsley and Smith, 1974). It is thus possible that the sharp, mid-Holocene peak in *Alnus* was caused by the presence of *Alnus* in the wetland habitat immediately surrounding the lake. This is further supported by the concurrent presence of *Alnus* macrofossil remains. Relatively low *Picea* pollen percentages are encountered since c. 4000 cal. yrs BP in comparison to other sites in Finnish Lapland (Salonen et al., 2013a). The WA-optima of *Picea* (15.2 °C) is 4th highest among the dominating taxa in the used CS and might thus to some extent have overestimated the reconstructed T_{jul} values during the late Holocene, despite its underrepresentation in the fossil samples compared to other sites in Fennoscandia.

Chironomids. The low temperatures reconstructed during the earliest Holocene (> 10 700 cal. yrs BP), i.e. during the deep glacial lake stage, appear to be driven by the cold- and deep-water taxa *Heterotrissocladius maeaeri*-type and *Tanytarsus lugens*-type. The former is also reported to have dominated the deep waters of the late-glacial Baltic Ice Lake (Luoto et al., 2010). The high T_{jul} values, which are reconstructed already during the existence of the deep glacial lake (until c. 10 570 cal. yrs BP), rise during the shallow glacial lake and peak during the initiation of Lake Loitsana with morphometric eutrophication (Shala et al., 2013). The T_{julC} remains relatively high following the

morphometric eutrophication at c. 10 200 cal. yrs BP. At c. 10 700–10 100 cal. yrs BP, there is a clear representation of taxa preferring more nutrient-rich conditions, e.g. the eutrophic littoral taxon *Polypedilum nubeculosum*-type (Raunio et al., 2010). This taxon thrives under shallow lake conditions, increases in littoral vegetation and/or higher nutrient availability, and might therefore cause the overestimation of T_{julC}. However, as this taxon occurs in high abundances already in the deep phase of the glacial lake (prior to 10 570 cal. yrs BP), the high T_{julC} values appear to be primarily climatically driven. This is further supported by the generally low presence of cold-water indicators with the exception of *Tanytarsus lugens*-type (Brooks et al., 2007), which nevertheless also clearly decreases in abundance since 10 700 cal. yrs BP. A slight overestimation of the T_{jul} values cannot, however, be ruled out as littoral vegetation was closer and transported to the coring site during 10 600–10 200 cal. yrs BP. It could thus be argued that this early Holocene peak in temperature was maintained or even prolonged by the morphometric eutrophication that followed and persisted until c. 9300 cal. yrs BP by causing an increase in several taxa with warm temperature optima (*Chironomus anthracinus*-type, *Cricotopus cylindraceus*-type and *Procladius*) and preference to higher nutrient conditions (Luoto, 2011). This seems, however, unlikely as temperature begins to decline during this period and continuing well into Stage 3B.

The low T_{julC} values (<13 °C) between c. 8700–6800 cal. yrs BP and 6000–4500 cal. yrs BP appear to be driven by high occurrences of *Corynocera ambigua* and *C. oliveri*-type (Fig. 4). The former has the third lowest WA temperature optimum of all dominating taxa in the CS and the latter has the lowest optimum with a value of 10.6 ± 1.4 °C (Fig. 6). The modern distribution of *Corynocera ambigua* in Finnish lakes is related to cold oligo-mesotrophic waters, but it is known to have a complex ecology

(Brodersen and Lindegaard, 1999). In the sediment sequence of Lake Loitsana it appears to be favoured by dense macrophyte communities of e.g. *Myriophyllum* (Shala et al., 2014, Fig. 2). Though generally considered a cold indicator, the stenotherm *Corynocera oliveri*-type has also been found in warmer lakes (Palmer et al., 2002) as well as associated to higher DOC concentrations (Gajewski et al., 2005; Medeiros and Quinlan, 2011). In the sediment record of Lake Loitsana it seem to be driven by increased DOC contents. The low T_{julC} from c. 8700 until 4500 cal. yrs BP, might thus to be an artefact caused by locally driven changes (e.g. river diversion). With the exception of *Corynocera ambigua*, which had high abundances throughout 6290-6790 cal. yrs BP, oligotrophic/cold-indicating taxa clearly decline or are completely absent while meso/eutrophic taxa such as *Dicrotendipes pulsus*-type and *Procladius,* with a WA-optima above 13 °C, clearly increase.

The gradually increasing and higher than present-day T_{julC} from c. 4500 cal. yrs BP until present is associated with declining abundances of cold-indicating *Corynocera ambigua* and *Paratanytarsus*. The most recent rise in T_{julC} values from c. 1800 cal. yrs BP to present, however, appears to be driven by increased abundances of warm-indicating *Cladotanytarsus mancus*-type and *Tanytarsus mendax*-type (Eggermont and Heiri, 2012), which also have a preference for shallow waters and nutrient-rich conditions (Brooks et al., 2007; Luoto, 2011). The T_{julC} of c. 15 ºC is therefore probably unrealistically high and driven by the further shallowing of the lake (e.g. Nyman et al., 2008).

[insert Figure 6.]

Diatoms. The diatom record at Lake Loitsana is characterized by mass-occurring Fragilariaceae (*Staurosira venter, S. construe*ns, *Pseudostaurosira brevistriata, Staurosirella lapponica, Staurosira binodis* and *Staurosirella pinnata*) throughout the Holocene (Fig. 5), comprising 55- 96% of each diatom assemblage. These taxa are generally considered as opportunistic and pioneering due to their wide range of ecological preferences and they often dominate lakes with disturbed conditions, for example, alpine proglacial lakes or recently deglaciated lakes (e.g. Lotter et al., 1999; Seppä and Weckström, 1999; Bigler et al., 2003; Schmidt et al., 2004). At lake Loitsana they seem to be favoured by the alkaline water and disturbances caused by fluvial/minerogenic influx as well as groundwater inflow from the nearby esker. WA-optima of the dominating Fragilariaceae taxa (Fig. 6) shows a clear pattern with generally low T_{julD} optima (~11.5–12.5 ºC), most likely resulting from the uneven distribution of CS sites along the temperature gradient. The low T_{julD} values throughout the Holocene appear to be an artefact of the mass-occurrence of Fragilariaceae and the distributional bias of the CS lakes towards the cold end of the temperature gradient. The high distance to the closest modern analogue, although rather constant throughout the Holocene, suggests that the similarities between the fossil samples and CS are low. Diatoms have been shown to capture Holocene climate variability (e.g. Pienitz et al., 1995; Korhola et al., 2000; Bigler, 2001; Weckström et al., 2006), although their sensitivity to other variables (e.g. pH, trophic state) complicates temperature reconstructions especially during time periods when the other variables are not constant (Anderson, 2000; Battarbee, 2000; Bigler and Hall, 2003; Laroque and Bigler, 2004). The general trend of the reconstruction, with higher temperatures during the early Holocene, and limited variation during the mid- and late-Holocene, is most likely to

some degree reflecting regional climate development, as diatoms depend on water-temperature for various processes (e.g. Pienitz et al., 1995 and references therein). However, the complex relationship between diatoms and environmental variables makes it difficult to disentangle the climate signal from the site-specific processes (e.g. pH, substrate, turbidity and trophic state) that have affected species distribution at Lake Loitsana (Shala et al., 2014).

Comparison of the T_{jul} reconstructions

A comparison of the reconstructed T_{jul} deviations from the present day value reveals that not only the absolute values but also the general trend differs considerably between the different proxies. While the pollen-based reconstruction displays low early Holocene (prior to 8200 cal. yrs BP) T_{jul} (~2 ºC below present day) and temperatures higher than present only after c. 8000 cal. yrs BP, the plant macrofossils and chironomids suggest high T_{jul} already in the early Holocene (prior to 8200 cal. yrs BP) with temperatures of at least 2 °C higher than present day prior to 10 500 cal. yrs BP (Fig. 7). Diatoms mirror this trend with higher temperature throughout the early Holocene, but with considerably lower values (around 12.8 °C).

[insert Figure 7.]

Local presence of plants is generally inferred from plant macrofossils although in some cases, also pollen from aquatic and wetland plants can be indicative of local presence (Birks and Birks, 2000). For example, *Typha latifolia* has been found to have a highly localized pollen dispersal (Krattinger, 1975; Ahee et al., 2015). In Lake Loitsana, scattered pollen occurrences of *Typha latifolia* and aquatic plants such as Nymphaeaceae were noted until c. 6500 cal. yrs BP and could be considered to indicate

local presence like plant macrofossil remains. This would suggest that temperatures were at least 15.6 °C, which is slightly higher than the reconstructed T_{julP}, although this falls within the margin of the sample specific errors. Also T_{julC} displays a trend with rising temperatures around 6500 cal. yrs BP, although the values are, in similarity with $T_{julD,}$ below present day temperature throughout middle Holocene (8200-4200 cal. yrs BP).

While plant macrofossils suggest at least comparable T_{jul} throughout the late Holocene (4200 cal. yrs BP to present), T_{julP} and T_{julC} reconstructions indicate higher than present T_{jul} temperatures (Fig. 7).

The somewhat different T_{jul} reconstructions based on different biological proxies revealed that local processes seem to have a strong impact on the results. While the macrofossil minimum T_{jul} reconstruction is mainly limited by taphonomic factors such as distance to the shore, water depth and inflow of streaming water to the coring site, the pollen record is clearly hampered by taphonomic differences between the modern and fossil data (Salonen et al., 2013a). Chironomid T_{jul} instead seem to be affected by macrophyte abundance, nutrient dynamics, and the general infilling of the lake, whereas the diatom T_{jul} is hampered by poor analogue situation due the mass occurrence of Fragilariaceae and the biased distribution of the CS lakes towards the cold end of the temperature gradient (Fig. 6).

Timing of the regional highest T_{jul} reconstructions

Early-Holocene warming suggested by chironomids and aquatic/wetland plant macrofossils and low T_{jul} suggested by pollen-based models has been observed at several locations in northern Fennoscandia (Väliranta et al., 2011b; Paus, 2013; Luoto et

al., 2014; Väliranta et al., 2015) and NE European Russia (Jones et al., 2011; Salonen et al., 2011; Väliranta et al., 2015). In contrast, pollen and macrofossil evidence of an early Holocene warming in NE Canada, where have been presented by Ritchie et al. (1983) who concluded that maximum summer temperatures prevailed at c. 10 000 a BP (uncalibrated). In central Norway, chironomid-based reconstructions show an early-Holocene warming with T_{jul} higher than present day values prior to 9000 cal. yrs BP (Paus et al., 2011), while in western Norway and northern Norway T_{julC} higher than present-day was observed prior to 10 000 cal. yrs BP (Brooks and Birks, 2001; Birks et al., 2012). Pine stomata preserved in the late glacial sediments and the presence of pine megafossils dated to 9500–9700 cal. yrs BP further support an early-Holocene warming (Paus et al., 2011). In NE European Russia, the chironomid record of Lake Kharinei also suggests high T_{jul} during the early Holocene and is contrasting with the T_{julP} (Fig. 7), while the presence of aquatic macrofossils such as *Elatine hydropiper* and *Potamogeton* spp reflect warm conditions during the early Holocene (Jones et al., 2011).

The high T_{julM} and T_{julC} values coincide with the early-Holocene high summer insolation level. In contrast to higher-than-present summer insolation, the early Holocene winter insolation was approximately 28% lower (~5 W/m^2) than present day (Berger and Loutre, 1991). The seasonal insolation deviation where the summer insolation was 10% higher and winter 28% lower than today around c. 11 000 cal. yrs BP, supported by the chironomid-inferred continentality-index (Self et al., 2011; Engels et al., 2014), suggests increased seasonality and more continental early Holocene conditions (Fig. 7). The early Holocene warming is also consistent with increased sun

spot activity (Solanski et al., 2004) as well as high summer sea-surface temperatures (SST) from the Barents Sea (Fig. 7).

To summarise, despite a relatively poor fit of the chironomid fossil samples to the closest modern analogue, the early-Holocene July warming appears to be significant and is supported by the independent macrofossil-based minimum T_{jul} estimates. The observed inconsistencies between T_{julP} and the chironomid/macrofossil-inferred T_{jul} appear to be mainly related to the overrepresentation of locally dispersed pollen types during the early Holocene, which have low modelled temperature optima due to their common occurrence in the NE European tundra region, but which also occur as elements of wetland habitats in a range of climates. In the sediment record of Lake Loitsana these cold-indicator pollen taxa are more likely associated with a wetland habitat immediately surrounding the lake. This inference is supported by the abundant preservation of plant macrofossils representing the same taxa. As the higher temperatures (i.e. > present day value) are driven mainly by the occurrence of tree pollen (e.g. *Tilia*, *Ulmus*, *Corylus*, *Carpinus*, *Quercus*, *Pinus*), the increasing T_{julP} values during the mid-Holocene might well be the result of a delayed response of the terrestrial vegetation due to e.g. soil maturation processes (Väliranta et al., 2011a, 2015).

Conclusions

Holocene July air temperature history of a northern boreal Lake Loitsana, Finland was reconstructed using multiple proxies (plant macrofossils, pollen, chironomids, and diatoms). The comparison between the different reconstructed temperature histories revealed that not only the absolute values, but also the general trend differs considerably between the different proxy-based reconstructions. While pollen-based temperatures

follow the classical trend of gradually increasing early Holocene temperatures with a mid-Holocene maximum, the aquatic/wetland assemblages reconstruct higher than present temperatures already during the early Holocene, i.e. at the peak of summer insolation. Both the aquatic/wetland macrofossils and chironomids suggest T_{jul} about 2 °C higher than present-day, whereas T_{julP} is approximately 2 °C lower than present-day and T_{julD} remains below present-day value, throughout the Holocene.

Since all the used proxies have some shortcomings regarding their use in palaeolimnological research it is essential to acknowledge them and carefully evaluate their impact on the final results. We show that during specific time windows all the climate reconstructions are substantially influenced at by local factors in addition to the underlying trend in regional climate. However, our study also highlights the considerable promise and benefits of multi-proxy datasets in palaeoclimate reconstruction, e.g. to identify outlier reconstructions and to exploit the most robust climate proxies in each time window.

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Figure caption

Figure 1. Map of the study site showing A. the location of the study site in Finland; B. the location of Lake Loitsana, coring point and geomorphology of the area (modified from Johansson (1995)), and C. climatogram showing mean monthly precipitation and temperature for the time period of 1971-2000 for Savukoski (67°17'N, 28°10'E, 193 m a.s.l.). Data were obtained from the Finnish meteorological institute.

Figure 2. A summary of the terrestrial vegetation development (Salonen et al., 2013a) and local development of Lake Loitsana (Shala et al., 2014). The carbon content (C_{org}) of the sediments, C/N ratio and selected local elements are included. Macrofossil remains (black silhouette) are presented as bars showing concentrations (amount/10cm^3) or as relative abundances; + = rare, ++ = occurring, +++ = abundant, ++++ = dominant, +++++ = main constituent of the sample. Microfossils (grey silhouette) are represented by graphs; phytoliths (%, relative to diatoms), *Pediastrum* (%, relative to pollen landsum).

Figure 3. Minimum T_{jul} based on presence of aquatic/wetland plants (T_{julM}) and pollen-based T_{jul} reconstruction using a two-component weighted averaging-partial least squares (WA-PLS) regression. The indicator species used to infer minimum T_{julM} are; 1 = Nymphaea (13.49 ºC), 2 = narrow-leaved *Potamogeton* spp such as *P. filiformis* (13.61 ºC), 3 = *Callitriche cophocarpa* (13.65 ºC), 4 = *Callitriche hermaphroditica* (14,0 ºC), 5 = *Glyceria lithuanica* (15.65 ºC) and 6 = *Typha* (15.69 ºC). Closest modern analogue (C.M.A.) of each fossil sample is calculated using the squared chord distance in order to assess the fit between the fossil and modern calibration set and LOESS

smoother (span 0.25, one robustifying iteration) is added to the T_{jul} reconstruction. Lake development (Local stages) and Pollen Zones generalized from Fig. 2, selected pollen taxa (%; grey silhouette) and macro/microfossil remains (dashed line) that confirm local presence of the plants are also included.

Figure 4. Chironomid-based T_{jul} reconstruction (T_{julC}) using a two-components WA-PLS regression. The fit of the fossil and calibration set is estimated using the squared chord distance to calculate the closest modern analogue (C.M.A.) of each fossil sample. LOESS smoother (span 0.25, one robustifying iteration) is added to the T_{julC}. Lake development (Local stages), generalized from Fig. 2, and selected chironomid taxa are included.

Figure 5. Diatom-based T_{jul} reconstruction using a two-components WA-PLS regression. The fit of the fossil and calibration set is estimated using the squared chord distance to calculate the closest modern analogue (C.M.A) of each fossil sample. LOESS smoother (span 0.25, one robustifying iteration) is added to the T_{julC}. Lake development (Local stages), generalized from Fig. 2, and mass-occuring Fragilariaceae are included.

Figure 6. The distribution of lakes along the sampled temperature gradients of the diatom calibration-set (7.9-15.7˚C), chironomid calibration-set (7.9-17 ˚C) and pollen calibration-set (9.0-17.3 ˚C) and mean July air temperature optima for the most common taxa occurring in the fossil data. T_{jul} optimum for the different taxa was calculated using the WA-approach.

Figure 7. Holocene lake proxy-based temperature reconstructions on the fossil record of Lake Loitsana. The T_{jul} reconstructions are here compared to the T_{julP} and T_{julC} reconstructions at Lake Kharinei (Jones et al., 2011; Salonen et al., 2011), the 60N summer and winter insolation (Berger and Loutre, 1991) and Barents Sea SST at 75N (Hald et al., 2007). Chironomid-inferred continentality index for both Lake Loitsana (Engels et al., 2014) and Lake Kharinei (Jones et al., 2011) are also included.

SUPPLEMENTARY INFORMATION to "Comparison of quantitative Holocene temperature reconstructions using multiple proxies from a northern boreal lake"

Shala S, Helmens KF, Luoto TP, Salonen JS, Väliranta M, Weckström J.

Holocene lake development

Sedimentation in the Loitsana basin initiated prior to 10 700 cal. a BP (Shala et al., 2014). The glacial lake that took form following the early Holocene deglaciation of the Sokli area was initially deep and covered extensive areas (Local Stage 1). The initiation of glacial lake drainage at c. 10 600 cal. a BP, resulting from the deglaciation of the Nuortti river canyon, caused a dramatic lowering in lake level, placing a smaller and shallowing glacial lake in a restricted catchment (Stage 2). After the final glacial lake drainage and formation of Lake Loitsana at c. 10 200 cal. a BP (beginning of Stage 3), a morphometric eutrophication (Stage 3a) occurred as a result of the decrease in lake volume and rapid infilling. This event lasted until c. 9500 cal. a BP and was followed by lake stratification starting at c. 9300 cal. a BP (Stage 3B). During its initial phase of infilling the Lake Loitsana was deep and received fluvial input from the Soklioja (Stages 3-4A). The infilling of the southern part of the Loitsana basin resulted in the redirection of the Soklioja at c. 6500 cal. a BP and wetland expansion (Stage 4B). The on-going infilling, although with reduced sedimentation rates, caused further shallowing of the lake throughout Stage 5 and 6. The lake was mainly groundwater fed from the adjacent esker from c. 4300 cal. a BP onwards (Stage 6).

The deep glacial lake was initially characterised by high influx of minerogenic sediments and a poor aquatic flora (Stage 1). As the ice-sheet retreated further away

from the coring-site, shore erosion, phytolith abundance and species diversity of diatoms, chironomids and aquatic macrophytes increased. The shallow glacial lake (Stage 2), was also characterised by occurrences of wetland/shore vegetation. Following the river diversion, in-lake vegetation seems to have become less diverse.

Organic carbon content (C_{org}) is generally low during the deep glacial lake (Stage 1) and increases gradually during the shallowing glacial lake and initial stage of Lake Loitsana (Stages 2-3A). Only minor variations in C_{org} (~7–15%) are observed throughout Stages 3B-5 with the exception of Stage 4B when the redirection of the Soklioja at c. 6500 cal. a BP resulted in an increase in C_{org}. During Stage 6, a similar increase in $C_{org,}$ (~ 17–37 %) is recorded, most probably reflecting low minerogenic input from the catchment as well as the high aquatic macrophyte abundance.

Regional Holocene vegetation development

A simplified pollen record from the Holocene was first published in Salonen et al. (2013). The entire terrestrial vegetation record, complemented with macrofossil data are presented in Fig. 1. Four pollen zones were distinguished (Zones I-IV).

During the initial stages of lake formation, i.e. prior to 10 500 cal. a BP (Pollen Zone I), the vegetation surrounding Loitsana consisted mainly of shrubs (*Betula nana*, Ericaceae and *Salix*) and herbs. The latter included a variety of light demanding helophytes such as Asteraceae (*Artemisia*, *Inula salicina*), Brassicaceae (*Rorippa palustris*), Caryophyllaceae, Chenopodiaceae and Polygonaceae (*Polygonum bistorta* type, *Rumex acetosella*). Seeds of *Carex* suggest that at least part of the Cyperaceae pollen is of local origin from a nearby wetland. Similarly, *Glyceria lithuanica* seed and pooid phytoliths indicate that also part of the grass pollen in Zone I had a local source. The vegetation was thus rather open during Zone I with tree-type *Betula*

locally present as suggested by the occurrence of seeds as well as high percentages of pollen (up to 40%). Zone II pollen assemblages (c. 10 200–9200 cal. a BP) indicate the presence of birch forest in the Sokli area. Macroscopic *Equisetum* remains that are present throughout Zone II indicate a local wetland source same as during Zone I (Fig. 1), whereas ferns, including *Athyrium*, and *Dryopteris* types, are well represented in the pollen record during Zone II-B.

The establishment of pine-birch forest (beginning of Zone III) occurred at c. 9200 cal. a BP. Zone III is further characterised by a near coninous presence of long-distance transported pollen of *Corylus* and *Ulmus*. *Alnus* as well as the herb *Filipendula* are well represented during Zone III-B (c. 8000–4000 cal. a BP). An increase in *Picea* pollen is observed during the last c. 4000 cal. a BP (Zone IV).

Figure captions

Supplementary Figure 3. Pollen and macrofossil diagram for terrestrial taxa from the Holocene sediment succession of Lake Loitsana. Macrofossil remains (green) are presented as bars showing concentrations (amount/10 cm^3) or as relative abundances; + = rare, ++ = occurring, +++ = abundant. Microfossil (pollen and spores) abundances are shown with grey silhouette curves, single samples with percentage values < 1% are represented by dots.

References

Salonen JS, Helmens KF, Seppä H and Birks HJB (2013) Pollen-based palaeoclimate reconstructions over long glacial–interglacial timescales: methodological tests based on the Holocene and MIS 5d–c deposits at Sokli, northern Finland. *Journal of Quaternary Science* 28: 271-282.

Shala S, Helmens KF, Luoto TP, Väliranta M, Weckström J, Salonen JS and Kuhry P (2014) Evaluating environmental drivers of Holocene changes in water chemistry and aquatic biota composition at Lake Loitsana, NE Finland. *Journal of Paleolimnology* 52: 311-329.

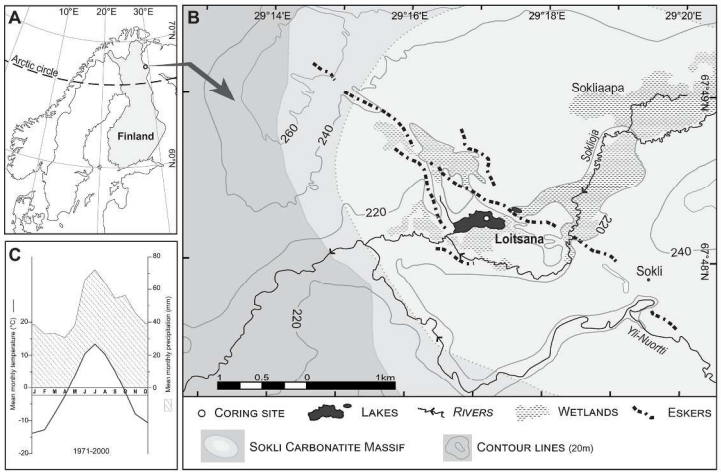

Figure 1. Map of the study site showing A. the location of the study site in Finland; B. the location of Lake Loitsana, coring point and geomorphology of the area (modified from Johansson (1995)), and C. climatogram showing mean monthly precipitation and temperature for the time period of 1971-2000 for Savukoski (67°17'N, 28°10'E, 193 m a.s.l.). Data were obtained from the Finnish meteorological institute.
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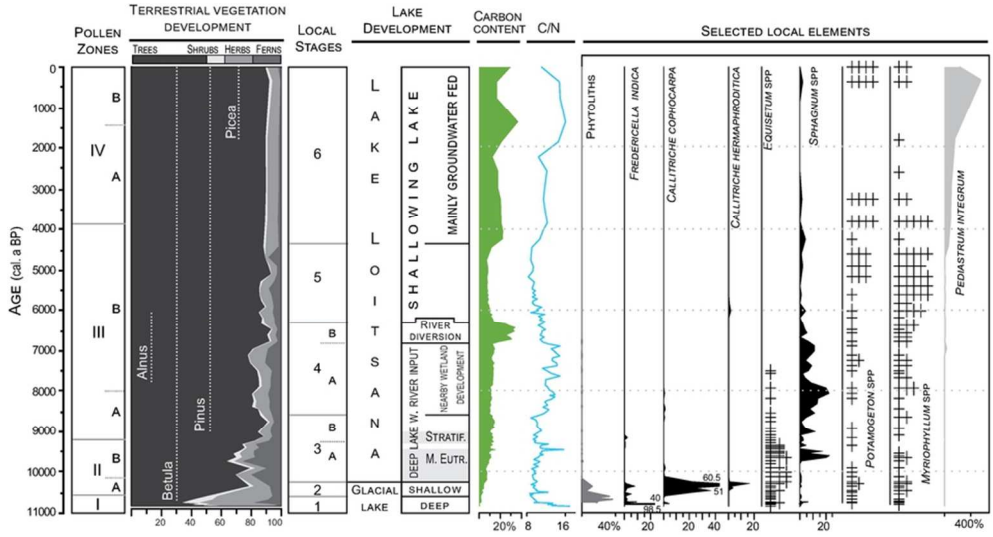

Figure 2. A summary of the terrestrial vegetation development (Salonen et al., 2013a) and local development of Lake Loitsana (Shala et al., 2014). The carbon content (C_{org}) of the sediments, C/N ratio and selected local elements are included. Macrofossil remains (black silhouette) are presented as bars showing concentrations (amount/10 cm^3) or as relative abundances; + = rare, ++ = occurring, +++ = abundant, ++++ = dominant, +++++ = main constituent of the sample. Microfossils (grey silhouette) are represented by graphs; phytoliths (%, relative to diatoms), Pediastrum (%, relative to pollen landsum).
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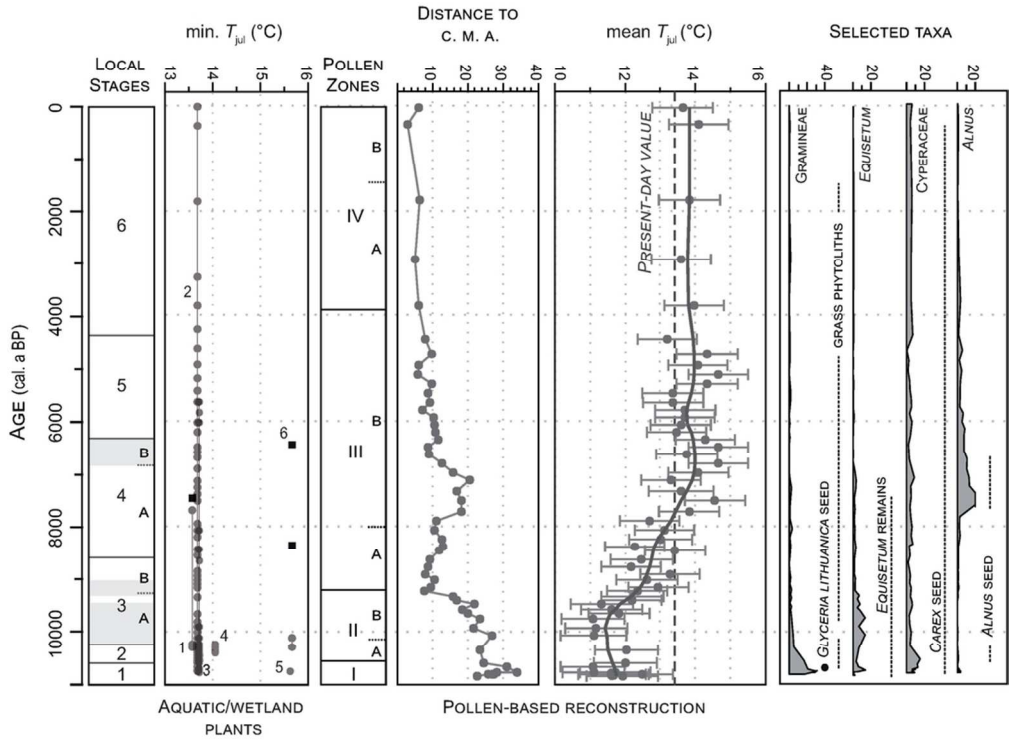

Figure 3. Minimum T_{jul} based on presence of aquatic/wetland plants (T_{julM}) and pollen-based T_{jul} reconstruction using a two-component weighted averaging-partial least squares (WA-PLS) regression. The indicator species used to infer minimum T_{julM} are; 1 = *Nymphaea* (13.49 ºC), 2 = narrow-leaved *Potamogeton* spp such as *P. filiformis* (13.61 ºC), 3 = *Callitriche cophocarpa* (13.65 ºC), 4 = *Callitriche hermaphroditica* (14,0 ºC), 5 = *Glyceria lithuanica* (15.65 ºC) and 6 = *Typha* (15.69 ºC). Closest modern analogue (C.M.A.) of each fossil sample is calculated using the squared chord distance in order to assess the fit between the fossil and modern calibration set and LOESS smoother (span 0.25, one robustifying iteration) is added to the T_{jul} reconstruction. Lake development (Local stages) and Pollen Zones generalized from Fig. 2, selected pollen taxa (%; grey silhouette) and macro/microfossil remains (dashed line) that confirm local presence of the plants are also included.
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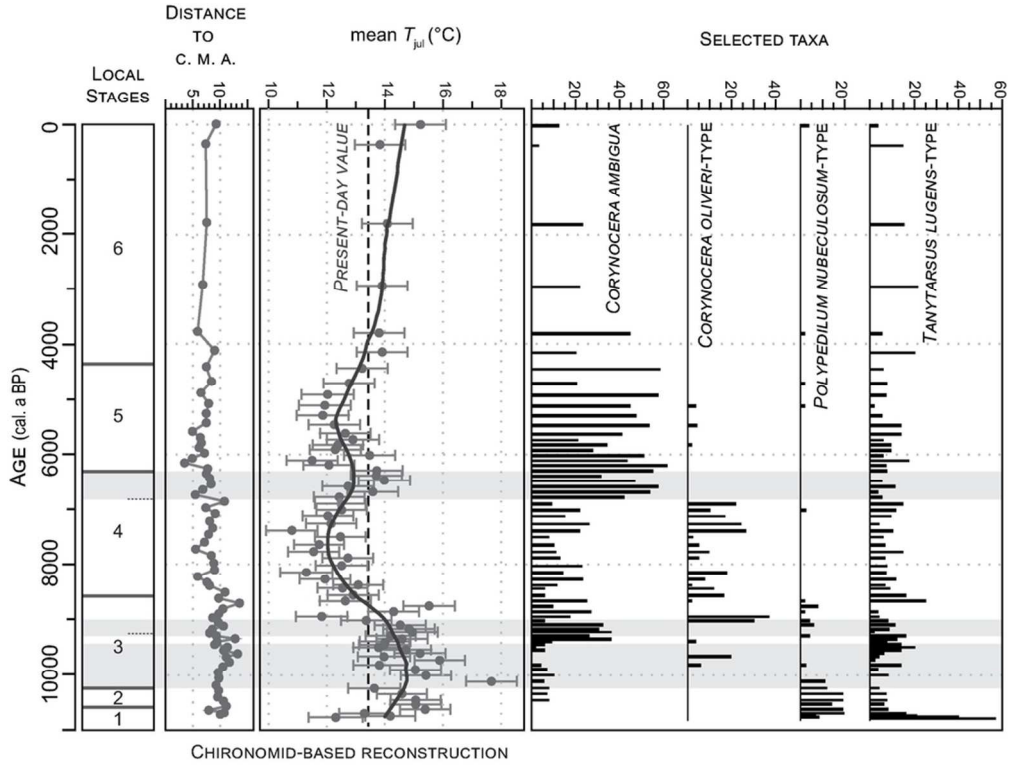

Figure 4. Chironomid-based T_{jul} reconstruction (T_{julC}) using a two-components WA-PLS regression. The fit of the fossil and calibration set is estimated using the squared chord distance to calculate the closest modern analogue (C.M.A.) of each fossil sample. LOESS smoother (span 0.25, one robustifying iteration) is added to the T_{julC}. Lake development (Local stages), generalized from Fig. 2, and selected chironomid taxa are included.
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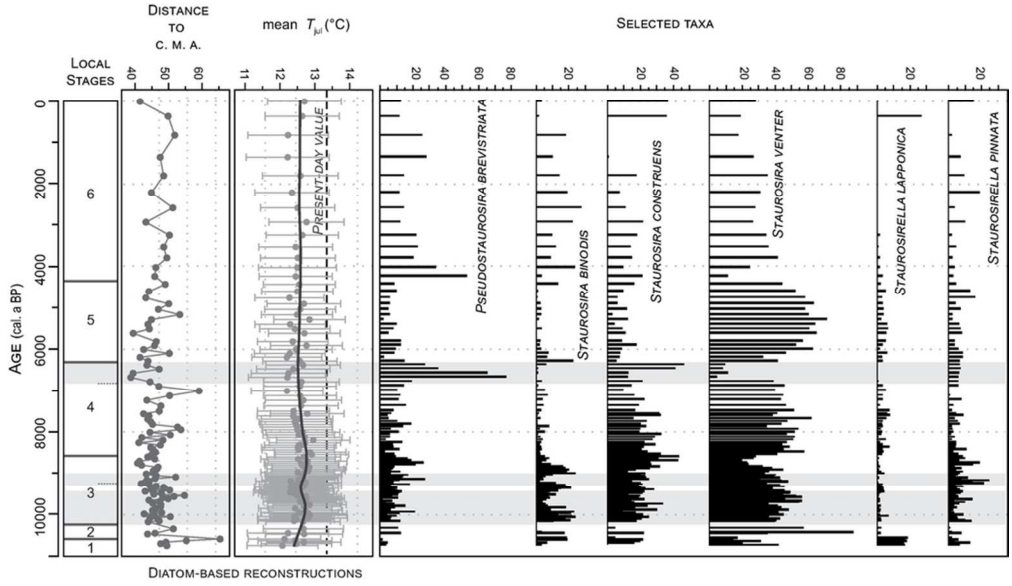

Figure 5. Diatom-based T_{jul} reconstruction using a two-components WA-PLS regression. The fit of the fossil and calibration set is estimated using the squared chord distance to calculate the closest modern analogue (C.M.A) of each fossil sample. LOESS smoother (span 0.25, one robustifying iteration) is added to the T_{julD}. Lake development (Local stages), generalized from Fig. 2, and mass-occuring Fragilariaceae are included.
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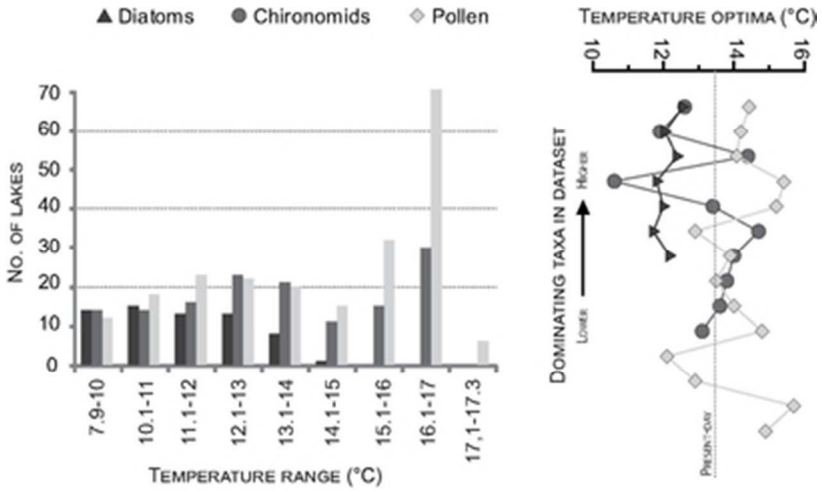

Figure 6. The distribution of lakes along the sampled temperature gradients of the diatom calibration-set (7.9-15.7°C), chironomid calibration-set (7.9-17 °C) and pollen calibration-set (9.0-17.3 °C) and mean July air temperature optima for the most common taxa occurring in the fossil data. T_{jul} optimum for the different taxa was calculated using the WA-approach.
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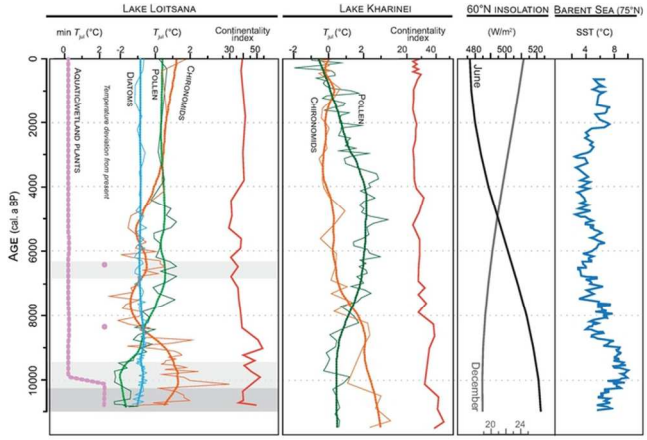

Figure 7. Holocene lake proxy-based temperature reconstructions on the fossil record of Lake Loitsana. The T_{jul} reconstructions are here compared to the T_{julP} and T_{julC} reconstructions at Lake Kharinei (Jones et al., 2011; Salonen et al., 2011), the 60°N summer and winter insolation (Berger and Loutre, 1991) and Barents Sea SST at 75°N (Hald et al., 2007). Chironomid-inferred continentality index for both Lake Loitsana (Engels et al., 2014) and Lake Kharinei (Jones et al., 2011) are also included.
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